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DNA EMP AWARENESS COURSE NOTES

Supplement to Third Edition

IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616

31 July 1978

Topical Report for Period January 1978—July 1978

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EMP Environment
EMP Systems Degradation Modes
EMP Interaction and coupling
EMP Design Practices
EMP Testing
EMP System Hardening

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

These notes are primarily intended as a guide for the individual attending the DNA EMP Awareness Course. The text serves as an engineering introduction to the EMP systems design problem and provides a survey of techniques suitable for solving this hardening problem. The text discusses all aspects of EMP, from the environment through system design and testing.

PREFACE

Supplement to Third Edition

This supplement to the Third Edition of the DNA "EMP Awareness Course" Notes is provided to maintain the course and the course notes current. The Third Edition of the Awareness Course Notes were written with primary emphasis given to introducing the generation and systems effects of EMP fields from high altitude bursts. This supplement treats the source region EMP, the MHD EMP and SGEMP and discusses the impact and importance of these effects for tactical, strategic and exoatmospheric systems.

This supplement was edited, in part, from material provided by the Mission Research Corporation, Santa Barbara, California. Recognition is due Mr. W. Hart and Dr. C. Longmire for providing much of the material in this volume.

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July 1978

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SECTION I

SOURCE REGION, EXOATMOSPHERIC, AND MHD EMP CONSIDERATIONS

1.1 INTRODUCTION

The DNA "EMP Awareness Course Notes" - Third Edition, treats the classical EMP coupling problem where electromagnetic fields are generated in one part of space and propagate through an intervening medium to a system located at relatively large distances from the burst location, that is, outside the EMP source region or gamma deposition region.

Further, the Third Edition treats only the propagated EMP fields generated by the prompt gammas. Other forms of EMP, such as Magnetohydrodynamic EMP (MHD EMP), with completely different characteristics are also generated and are important to a limited class of systems.

The environment seen by exoatmospheric systems (i.e., operating outside the atmosphere), such as satellite systems, was not discussed in the Third Edition of the notes. Here again, the environment characteristics are significantly different and warrant separate discussion.

The purpose of this supplement to the Third Edition is to discuss the systems mission and deployment factors where these environments should be considered, generation of these environments, and a discussion of how these environments interact with and couple to systems of interest.

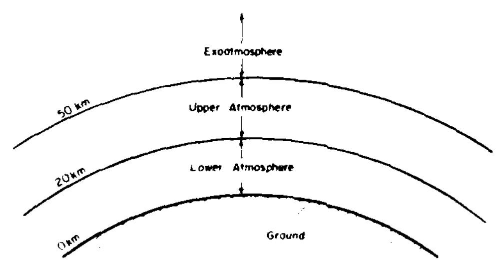
SECTION II

SYSTEM CONSIDERATIONS

For purposes of establishing the EMP environments of interest, the mission of a given system can be described in terms of its operational deployment and required operational survivability. Consideration of the operational altitude determines what burst locations are of importance in terms of the EMP generation. The system nuclear hardness refers to the amount of protection the system has to nuclear weapons effects (i.e., blast and shock, radiation, thermal, EMP, etc.). The categories and bounds for both of these elements of the mission are described below.

2.1 OPERATIONAL REGIME

The operational regime (operating altitude) for purposes of this discussion has been divided into four general categories: ground, lower atmospheric, upper atmospheric, and exoatmospheric altitude. This categorization is depicted in the figure which indicates the approximate altitudes bounding each category.



CATEGORIES OF SYSTEM OPERATING REGIONS

The ground category includes systems operating on or under the earth. Systems in this category would include buildings, silos and vehicles such as trucks, tanks, ships, etc. The lower atmospheric category is bounded between 0 km and 20 km altitude. Systems in this category would include aircraft and missiles during boost and terminal phases. The upper atmospheric category is bounded between 20 km and 50 km altitude. Systems operating in this category would be primarily missiles. The fourth category, exoatmospheric, is any altitude greater than 50 km. Systems operating in this altitude regime are satellites and missiles. Many systems operate in more than one of these categories during their mission. These altitude regimes are approximate. There is no clear-cut division.

2.2 SYSTEM HARDNESS

System hardness is the second element to be considered in the mission classification. For purposes of this discussion we will classify system hardness into two categories: hard and soft. Hard systems are those that have been intentionally designed to operate in a specified nuclear environment. Soft systems are those that are not designed to operate in a nuclear environment and their hardness level is that inherently afforded by the basic structure.

All critical elements of the system with regard to performing the mission must be considered in establishing the hardness level. For example, if the system is a manned system, and the man is required for performance of the mission, he is a critical element of the system.

In establishing this hardness level, all nuclear weapons effects must be considered. These include blast overpressure, shock, thermal radiation, gamma, neutron and x-ray radiation and EMP in the operating regime. These factors will determine the survivable range from the burst location. This is termed the balanced hardness approach in that the system is hardened to all nuclear weapons environments that exist at a suvivable location.

2.3 EMP ENVIRONMENT CLASSIFICATION

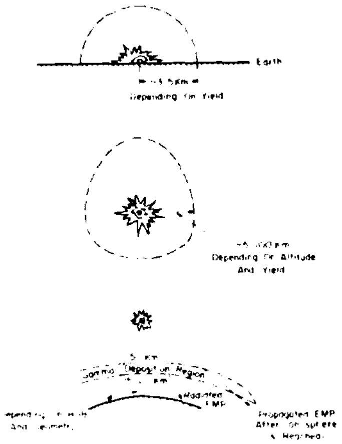
In order to classify the EMP threat, the type of nuclear burst, and the relative locations of the burst and system must be identified. There are three basic types of bursts: surface/near surface, air and high-altitude (exoatmospheric). The relative locations of the burst and the system determine the EMP environment. A simplified Mission/Environment Matrix is shown in the table which indicates the category of EMP environment that will be experienced, i.e., deposition region, radiation region, and propagation region. The radiation region is that where the EMP propagates along an unobstructed line of sight from the burst location, i.e., "directly propagated". Propagated EMP region is where the EMP has been modified by intervening media, such as the ionosphere or the earth.

			EMP Environment								
			Deposition			Radiation			Propagation		
			Surface	Air	High Altitude	Surface	Air	High Altitude	Surface	Air	High Altitude
Mission	Hard	Ground									
		Lower Atmosphere									
		Upper Atmosphere									
		Exo Atmosphere									
	Soft	Ground									
		Lower Atmosphere									
		Upper Atmosphere									
		Exo Atmosphere									

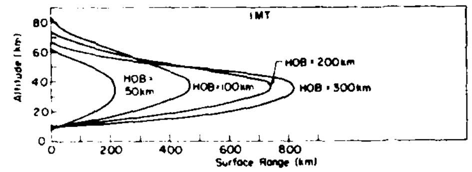
MISSION/ENVIROMENT MATRIX

The shape and spatial extent of the EMP signal generated by a nuclear detonation depend primarily on the height of burst (HOB). There is no clear-cut division between the types of burst. Nominally, a surface/near surface burst occurs at altitudes between 0-2 km. Air bursts occur at altitudes between 2-20 km, and high-altitude bursts above 30 km. Between 20-30 km, the EMP will have approximately the same characteristics as the air-burst.

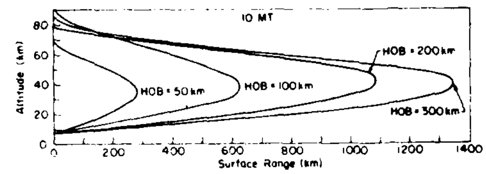
The EMP from a nuclear burst is generated in that region of space where the gamma radiation from the weapon deposits its energy and creates electrons through Compton collisions. For purposes of this discussion, the deposition region is defined as the region of space where a conductivity of 10^{-7} mho/m or greater is created. A rough idea of the extent of the EMP source regions or gamma deposition regions for surface, air and high-altitude bursts are shown in the figure.



EMP SOURCE REGION



DEPOSITION REGION FOR A 1 MT BURST AT HOBS OF 50, 100, 200 AND 300 KM



DEPOSITION REGION FOR A 10MT BURST AT HOBS OF 50, 100, 200 AND 300 KM

The extent of the EMP source region (or gamma deposition region) for the high-altitude burst varies greatly with the HOB and yield. This dependence and the size of the EMP source region for two yields and four burst heights is shown in the following figures.

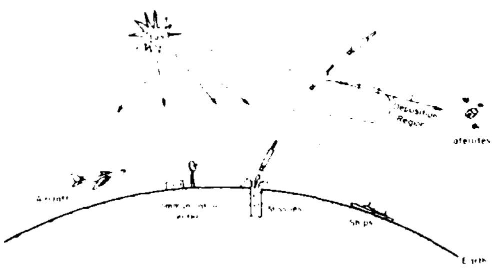
Outside of the gamma deposition region, the EMP threat can be treated as a radiated field. The radiated EMP for the various burst categories is discussed in Section III of the Third Editio. of the notes. As can be seen from these figures, the size of the source region for surface and air bursts is dependent on yield, although this dependence is not linear (that is, doubling the yield does not double the size of the source region). This is due to the fact that the extent of the source region is highly dependent on the gamma absorption distance (stopping range) which is directly proportional to the air density and initial gamma energy. It should be noted that x-rays also produce ionization and therefore contribute to the source region fields. However, the x-rays are lower energy than the gamma rays even though they constitute a much larger fraction of weapon output and are absorbed in very short distances in the surface or air burst case and are not a major factor. This dependence on gamma absorption can easily be seen by comparing the surface and air burst source region size. As the burst point is elevated above the earth, the air density decreases, and the source region increases for the same device yield. The relationship and transformation of the weapon outputs in terms of percent of yield is shown in the following table.

TRANSFORMATION OF WEAPON ENERGY NEAR THE EARTHS SURFACE

Weapon Output	Transformation	% of Yield
X-Rays, Debris →	Blast	~ 50
	Thermal	~ 35
Gamma (γ), Neutron (m) →	EMP	~ <1
	Gamma (γ), Neutron (m)	~ <3
	Fallout, Local Heating	~ 10

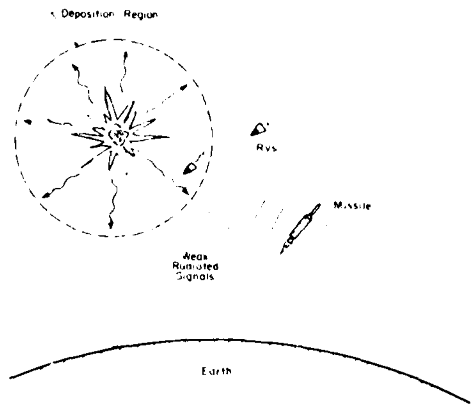
2.4 SYSTEM HARDENING IMPLICATIONS

As can be deduced from the previous discussion, high-altitude radiated EMP is a threat to all systems, hard and soft. The high-altitude source region EMP is primarily a threat to missiles and reentry vehicles (RV's) which pass through it. Since the radiated EMP from a high-altitude burst is a threat to all systems it provides a good baseline for comparison with other threat environments. The following figure provides a simple illustration of the high-altitude EMP and the types of systems it can affect.



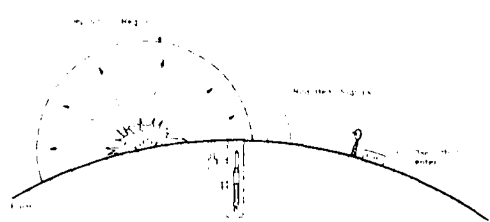
HIGH-ALTITUDE EMP

The radiated EMP from an air burst is very weak compared to the high-altitude or surface burst. Therefore, the principle threat from the air burst is to hardened systems in the atmosphere which pass through the gamma deposition region. The fields in the source region are high level as for other burst locations. The air burst case is depicted in the following figure.



AIR-BURST EMP

The surface-burst radiated EMP is also much weaker than the high-altitude radiated EMP. The frequency spectrum is also shifted placing greater emphasis on the lower frequencies (see Section III of the Third Edition of the notes). It can effect soft systems or systems with large coupling structures which would respond at the lower frequencies. The deposition region fields resulting from a surface burst are a threat to hardened systems, such as (1) strategic systems which are targeted (missile launch complexes), and (2) tactical systems which may become involved in a tactical nuclear engagement where low yield weapons will be detonated nearby. A simplified illustration of the surface burst and the systems affected by it are shown in the following figure.



GROUND-BURST EMP

SECTION III

ENVIRONMENT GENERATION AND CHARACTERISTICS

The basic EMP generation mechanisms are discussed in the Third Edition of the course notes, Section III and will only be briefly reviewed here. The purpose of this discussion is to present information on additional EMP environments not covered in the course notes. Specifically, the environments to be considered are: (1) the close-in environments; (2) the MHD-EMP; and (3) the space environment.

3.1 CLOSE-IN EMP ENVIRONMENT

Basic Physics

A nuclear detonation emits a flux of energetic photons (gamma and x-rays) which move away from the burst in the radial direction. They interact with the air molecules and create high-energy electrons by the Compton process. The rapid radial movement of these freed Compton electrons (e_c^-) creates a Compton electronic current.

As the Compton electrons travel, they give up their energy to the surrounding air molecules through inelastic collisions. The energy from these collisions liberates low-energy electrons from the air molecules, producing many electron/ion pairs. The liberated secondary electrons (e_s^-) produce an electrically conducting plasma around the burst. Since electromagnetic fields are generated by currents and/or charge distributions, the separation of Compton electrons from their positively charged parent air molecules generate an electromagnetic field. This field produces a conduction current in the conducting plasma around the burst.

Electromagnetics

The electromagnetics involved in EMP generation and propagation are governed by Maxwell's two curl equations:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu \vec{J} + \mu \varepsilon \frac{\partial \vec{E}}{\partial t}$$

where

$\vec{E}$ is the electric field intensity vector

$\vec{B}$ is the magnetic induction vector

$\vec{J}$ is the current density vector

μ is the permeability of the medium

ε is the permittivity of the medium

t is the real time.

The current density created by the nuclear burst must be determined before these equations can be solved for the electric and magnetic fields. The current density term can be broken into two components for the purpose of calculations. These are the driving current ($\vec{J}_D$) and the conduction current ($\sigma\vec{E}$), where σ is the conductivity:

$$\vec{J} = \vec{J}_D + \sigma\vec{E}$$

This driving current can be divided into three terms by virtue of the process that creates them.

$$\vec{J}_D = \vec{J}_c + \vec{J}_{pe} + \vec{J}_{pp}$$

where

$\vec{J}_c$ is the Compton current

$\vec{J}_{pe}$ is the photoelectric current

$\vec{J}_{pp}$ is the pair production current.

In the Compton process, resulting in the Compton current, the high energy photons scatter off an atomic electron giving the latter some recoil energy which reduces the scattered photon energy. The high energy photons, in the case of a nuclear detonation are the emitted gamma rays. In the case of the photoelectric effect, the photon disappears giving all its energy to the electron ejected from the atom. The photoelectric current is produced primarily by the emitted x-rays.

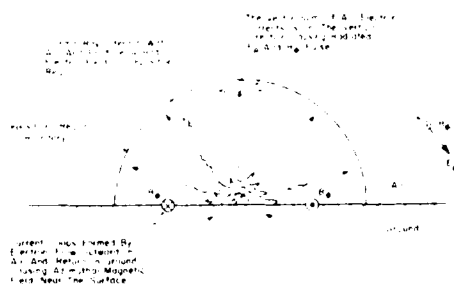
The gamma rays being the high-energy photons travel much further in air than the lower energy x-rays and therefore, the Compton electrons are the most important contributor to the driving current. The pair production current is usually negligible because of the high energies required for significant amounts of pair production and because the positive and negative currents will cancel, except in the presence of a magnetic field. The pair production mechanism is important in the calculation of conductivity (σ). It should be noted that the current generation is a function of time and consequently, the conductivity is a function of time. Further, the conductivity is a function of the electric field since this influences the mobility of the ions.

Boundary Conditions

The boundary conditions influence the creation of the electromagnetic fields. If the burst occurs in a homogeneous atmosphere, the current density is spherically symmetrical and does not produce a radiated field. In a surface burst asymmetries are introduced by the air/earth interface; in an air burst by the variation in atmospheric density; and in a high-altitude burst by the space/atmosphere interface.

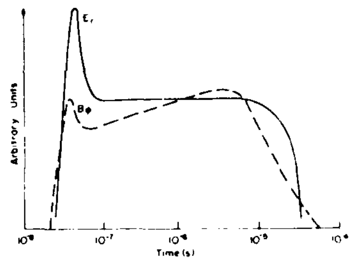
Field Generation and Characteristics

The surface burst case will be used to discuss the field generation. The charge separation resulting from the Compton process establishes a strong radial electric field ($\vec{E}_r$). The secondary electrons are acted upon by this electric field to produce the conduction current $\sigma\vec{E}$. Due to the presence of the earth and the higher conductivity of the earth, the conduction currents tend to flow back to the source through the earth giving rise to current loops, and an azimuthal magnetic field (B_ϕ) and the transverse electric field ($\vec{E}_\theta$).



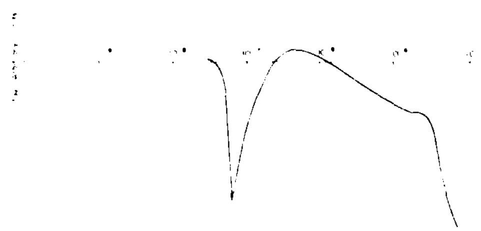
SIMPLE ILLUSTRATION OF SURFACE-BURST EMP

A general time history of the radial electric field (E_r) is characterized by a sharp peak and a long plateau. As distance from the burst is increased, the peak of the radial electric field is reduced and the initial rate of rise is slowed. The peak amplitude is on the order of 100's of kilovolts per meter. The azimuthal magnetic field is also shown. Peak amplitudes of 100's of gauss are present very close in and fall off rapidly with distance.



GENERALIZED TIME WAVEFORMS OF SURFACE-BURST RADIAL ELECTRIC FIELD (E_r) AND AZMUTHAL MAGNETIC FIELD ($B\phi$)

The E_θ field is the radiated field and is characterized by a short pulse and oscillating waveform in the far field. The E_θ field also falls off with distance from the burst in both the deposition region and outside it. The spike is on the order of 10's of kilovolts per meter or greater very close in (high overpressure regions, > ~ 25 psi).



GENERALIZED TRANSVERSE ELECTRIC FIELD ($E\theta$)

The radial field falls more rapidly with distance from the burst than the transverse field in the deposition region. The crossover (i.e., where $E_\theta > E_r$) is in the neighborhood of the 100 psi contour. The waveform of the radial field is also dependent on the observer (system location) altitude. As altitude is increased the peak amplitude changes only slightly but the plateau is reduced significantly for a change in altitude of a few kilometers.

A comparison of the EMP environments produced by a high altitude burst (HEMP) and the source region (SREMP) for both a strategic weapon and a tactical weapon are shown in the table.

As can be seen from the above discussion, the principal differences between the source region EMP problem and the radiated EMP problem are:

- Presence of ionizing radiation
- Spectral distribution of the energy
- Presence of Compton driving currents (J_c)
- Presence of conduction currents (σE)
- Area and volume of threat.

SREMP vs HEMP PROPERTIES

	HEMP Strategic	Y > 100 kt Strategic (300-10^3 psi)	Y < 100 kt Tactical (2-15 psi)
Fields	E 50 kV/m Hor.	100 - 800 kV/m	30 kV/m - 50 kV/m
	B E/η_o = 133 A/m $\doteq$ 1.67 gauss	100 gauss	1 gauss
Risetime	5 - 20 ns	5 - 20 ns	5 - 20 ns
Pulse Width	~ 1 μs	~ 50 - 100 μs	~ 50 - 100 μs
Compton Currents J_r	0	10^4 Amp/m^2	200 Amp/m^2
Air Conductivity	0	10^{-1} - 10^0 mho/m	10^{-3} - 10^{-4} mho/m
$\dot{\gamma}$	0	10^{12} rad(si)/sec	10^8 - 10^{10} rad(si)/sec
Effective Ground Area	10^7 km^2	(10^4 kV/m Minimum) 12 - 35 km^2	(10^4 kV/m Minimum) 3 - 12 km^2

In the EMP source region, the fields are not free space fields and therefore are not related by the intrinsic free space impedance. Separate calculations from Maxwell's equations are required to obtain the E and H fields.

Also of interest is the time history of these fields. The plateau stretches out to the millisecond region for these fields. This results in an enhancement of the low frequency spectral content of the SREMP as compared to the HEMP. This can result in additional coupling to a system if it is sensitive to the low frequency content. How these various characteristics interact with the system and their impact is discussed in Section 4.1.

Direct Radiation Interaction

In the EMP source region or gamma deposition region, consideration must also be given to direct interaction of the gamma rays, x-rays, and neutrons with the system. Of primary concern to systems within the atmosphere, with the exception of systems hardened to very high (>300 psi) overpressure levels, are the gamma rays and neutrons due to the limited range of x-rays in the atmosphere.

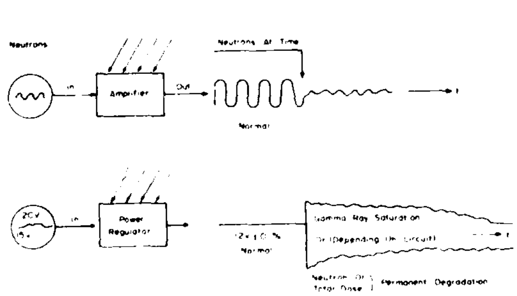
Initial Nuclear Radiation

One such direct interaction effect is TREE (Transient Radiation Effects on Electronics). Illumination of electronic components, especially semiconductors, with gammas and neutrons can result in degraded performance of the components, or the generation of photo currents in circuits resulting in system upset.

Transient radiation effects are associated principally with the component itself, that is, the capture area is the device area. Neutron irradiation results in such effects as displacement damage in materials, reduction of minority carrier lifetime in semiconductors, reduction in transistor gain, and an increase in leakage current. In terms of total gamma dose the effects are reduction in transistor gain, and increased leakage current. The gamma dose rate ($\dot{\gamma}$) results in the production, collection, and amplification of ionization currents (photocurrents). As mentioned, these effects are piece part related and control of these effects is achieved through parts selection and circuit design.

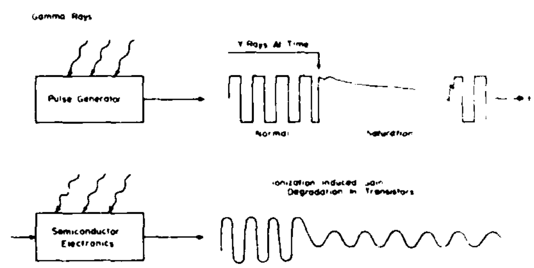
Shown are the effects of neutron irradiation on typical circuits. The neutrons degrade the transistor gain. In the amplifier circuit this results in reduced signal output, possibly to the point of functional failure. In the regulator circuit, the output (regulated voltage) might be much less than normal for the system. Gamma rays could also saturate the series regulator so that full power supply voltage is applied to the system causing component burnout.

SUMMARY OF CIRCUIT EFFECTS OF RADIATION-I



Gamma rays can also result in circuit saturation due to ionization currents or ionization-induced gain degradation in stransistors as depicted here.

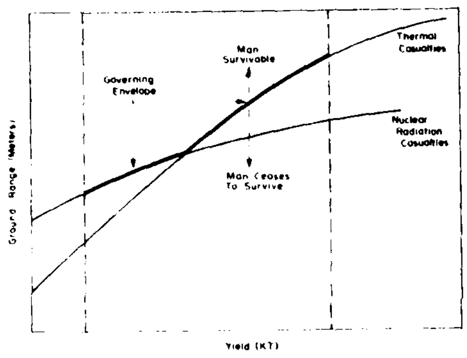
SUMMARY OF CIRCUIT EFFECTS OF RADIATION-II



This discussion is intended only to bring to light the need for consideration of radiation effects on electronic systems. These effects could easily be the limiting factor on system hardness in the EMP source region if they are not considered.

Another aspect of initial nuclear radiation is the effect on personnel. In manned systems, the tolerable radiation level (total dose) for early transient incapacitation (ETI) is usually specified. This level is dependent on range to the burst, weapon yield, and the protection (either inherent or designed in) afforded by the system. ETI due to nuclear radiation usually governs man survivability for low yield (tactical weapons < 100 kt) whereas blast and thermal effects usually govern for high yield (strategic weapons > 100 kt).

As in the case of SREMP the TREE environment is a function of the distance from the burst and the weapon yield. The initial nuclear radiation is reduced for increasing range and smaller weapon yields.



TYPICAL GOVERNING ENVELOPE (MANNED SYSTEM)

System Generated EMP

Another element of the source region environment is system generated EMP (SGEMP). SGEMP results from an interaction between the emitted photons and the material comprising the system enclosure. Photons incident on enclosures scatter electrons into and outside of the enclosure. These electrons, in turn, generate electromagnetic fields which can couple to internal cables and circuitry in the same manner as any EM wave.

The SGEMP voltages and fields depend on the cavity dimensions and the photon dose rate. As in the other cases discussed previously, the gamma dose rate is the principle consideration except for very hard systems or space systems which may be exposed to the x-ray fluence.

The significance of SGEMP can best be indicated by two simple examples.

In the first example, the photons are incident end-on to a cylinder whose radius r_o is much greater than the cylinder length. For this case, the maximum induced voltage and the maximum electric field are given by

$$V_{max} \cong 1.25 \times 10^{-6} \dot{\gamma} d^2, \text{ volts}$$

$$E_{max} \cong .5 \times 10^{-5} \dot{\gamma} d \text{ v/m},$$

where all units are MKS and $\dot{\gamma}$ is in roentgens/sec.

For a cavity with a thickness (d) of 2 meters, radius (r_o) of 5 meters and a gamma dose rate ($\dot{\gamma}$) of 10^9 rads/sec (1.14×10^9 roentgens/sec) which is in the range of $\dot{\gamma}$ for a tactical weapon, the maximum voltage and electric field are:

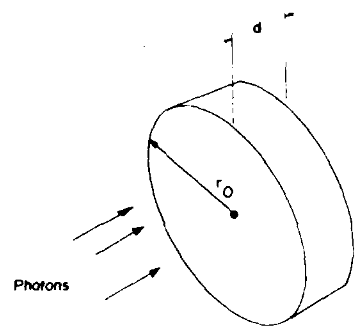
$$V_{max} \cong 5.7 \text{ kV}$$

$$E_{max} \cong 11.4 \text{ kV/m}$$

The B-field is given by:

$$B_{azimuthal} = 1.3 \times 10^{-14} \dot{\gamma} r_o \text{ webers/m}^2.$$

For the case above this results in a magnetic field (B-field) on the order of 7.4×10^{-5} webers/m^2 or H field of 58.7 amps/m.



PHOTONS END-ON INCIDENT TO A CYLINDER FOR $r_o \gg d$

Another case of interest is a long, thin cylinder illuminated broadside by photons, as shown in the following figure. In this case, the maximum electric field, voltage, and axial B-field are given by

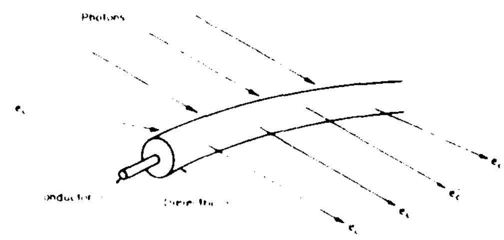
$$E_{max} \cong .5 \times 10^{-5} \dot{\gamma} r_o$$

$$V_{max} \cong .25 \times 10^{-5} \dot{\gamma} r_o^2$$

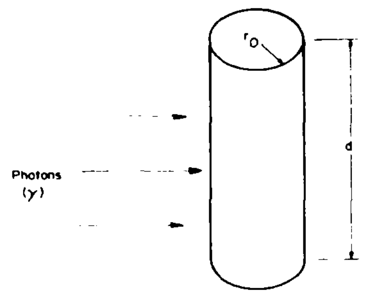
$$B_{axial} \cong 2.5 \times 10^{-14} \dot{\gamma} r_o.$$

For a cylinder radius of $r_o \approx .55$ m, the range of values for electric field, voltage, and magnetic fields is 4.7 to 55 kV/m, 1.3 to 15 kV, and 2.3 to 27.5 x 10^{-5} webers/m^2, respectively for a range of $\dot{\gamma}$ from 1.5 to 17.5 x 10^9 rads/sec (1.7 to 20 x 10^9 roentgens/sec).

It should be noted that these fields are calculated on the basis of an evacuated cavity. The difference between an air-filled and evacuated cavity is on the order of 5 percent for $\dot{\gamma} \cong 10^8$ roentgen/sec, and a factor of 3 for 10^{11} roentgen/sec. In any case, the values given here are worst case, insofar as the effect of the air is concerned.



IEMP - COMPTON CHARGING



PHOTONS BROADSIDE INCIDENT TO A CYLINDER FOR $r_o \ll d$

These results clearly show that the SGEMP fields must be considered in a tactical system analysis.

Internal EMP

Another type of direct radiation interaction is termed internal EMP (IEMP) or Compton charging. This phenomenon results from the direct impingement of energetic photons on cables, etc., resulting in the ejection from the cable of Compton electrons. These exiting electrons leave a net charge on the cable, resulting in an induced current. It should be noted that Compton electrons emitted from other surfaces may also enter the cable, but in all probability, the number exiting and entering would not be equal.

An example will illustrate the relative effects of the photon coupling and field coupling to a cable in a cavity.

Reference 5-7 discusses the photon coupling to cables, and also included is the case of a cable of characteristic impedance of 84 Ω located .5896 cm over a metal plane illumined by photons. The equivalent transmission line driver distributed current source for this case is on the order of $I_p = 4.3 \times 10^{-11}\ \dot{\gamma}$ amps/m, where $\dot{\gamma}$ is in rad/sec. This number was calculated on the basis of a cable in a conduit, and the source value for a cable over a ground plane will be within a factor of 5 or 6 of this value.

The corresponding SGEMP current source drive is given by

$$I_{SGEMP} = C \frac{\partial}{\partial t} \int_o^h E \, d\ell ,$$

where h is the height of the wire above the ground plane and C is the capacitance per unit length. Substituting for E from the previous section,

$$E_{max} = 0.5 \times 10^{-5}\ \dot{\gamma}\ d \text{ V/m}$$

d = thickness of the cylinder

we obtain:

$$I_{SGEMP} = Ch\left(.5 \times 10^{-5}\right) d \frac{\partial}{\partial t} \dot{\gamma} .$$

The relation between the photon current source I_p and the IEMP current source I_{IEMP} can then be written as

$$\frac{I_p}{I_{SGEMP}} = \frac{4.3 \times 10^{-11} \dot{\gamma}}{Ch \left(.5 \times 10^{-5}\right) d\frac{\partial}{\partial t} \dot{\gamma}}$$

For h = .5896 cm, and $C = 40 \times 10^{-12}$ farad/m and a rise time of 10^{-8}, we can get

$$\frac{I_p}{I_{SGEMP}} = \frac{.36}{d}$$

For this example, then, we can see that for d > .36 m, the SGEMP current source dominates the photon (IEMP) current source. Thus, it appears that as the cavity becomes larger, the SGEMP begins to dominate over the direct photon drive.

IEMP excitation of the transmission line also includes a distributed voltage source $\partial\phi/\partial t$, where ϕ is the magnetic flux per unit length linked by the transmission line and ground plane. This source was not included in the above analysis, but can be easily done if desired, using the expression for the B-fields given previously. The main point of this example is to show the approximate relationship between the effects of direct photon (IEMP) drive and SGEMP drive of cables inside a metallic enclosure.

There are many factors which determine the magnitude of undesired signals induced on a given cable by ionizing radiation. Radiation temperature, exposure level, temporal behavior and relative orientation with respect to the cable axis are significant parameters of the environment. Cable geometry, materials, exposed length and electrical configuration must also be considered in estimating the interference.

The analytical treatments are beyond the scope of these notes. They are treated in the references listed in Section V.

Synergism

In the EMP source region, the photons and EMP simultaneously illuminate the system. Since many analyses are performed on a "worst-case" basis, the question arises as to whether the effects of EMP and TREE can be treated separately or must they be considered in combination.

Four independent and reliable investigations have studied this problem at the component level (Vault at Harry Diamond Labs, Budenstein at Auburn University, Raymond at Northrop-MRC and Habing at Sandia Labs). The investigations by Vault on IC's showed no more than a factor of two (2) difference in individual environment failure levels and combined environment failure levels. Raymond also found only extremely weak evidence of synergism in IC's. Habing in a realistic environment test showed no synergism effect within a factor of two.

Budenstein performed investigations on two dimensional SOS diodes. These devices were specially fabricated to study current concentrations in back biased junctions as a function of current drive. Hot spot nucleation is a function of the current drive and junction geometry. Irradiation by gamma rays ($\dot{\gamma}$) results in the production of photocurrents (biasing the junction in the forward direction) which tends to cool the junction which results in an increase level for failure.

The net result of these studies is that no significant changes in failure levels for components occur due to synergistic effects.

At the circuit/system level, however, synergistic effects have been seen. These result from the photocurrent generation triggering conduction in the circuit/system which in turn permit the electrical pulses to cause upset or burnout. In this case, the synergistic effects can be eliminated by limiting the photocurrents through component selection or circuit design.

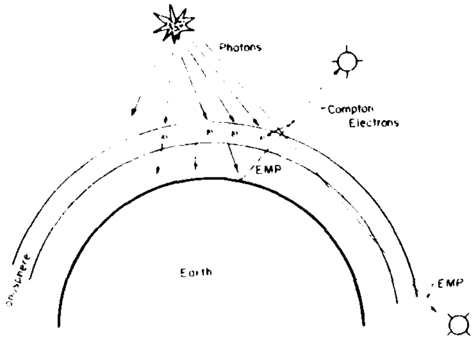
The simultaneous presence of external EMP, SGEMP and IEMP must also be considered. In this case, the resulting terminal voltages and currents will be a superposition of the individual voltages and currents. This superposition can be achieved in the frequency domain by taking the Fourier transforms of the individual voltages/currents, adding them with the proper phase relationships, and taking the inverse transform. Depending on the phase relationships, constructive or destructive interference of these waveforms may take place.

3.2 EXOATMOSPHERIC ENVIRONMENT

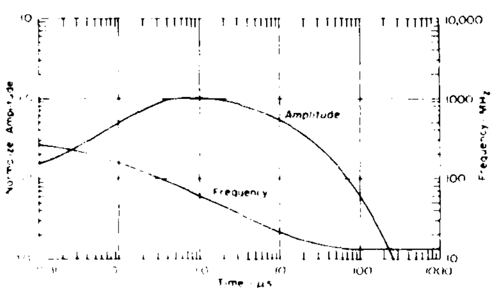
EMP Environment

The EMP environment at satellite altitudes results principally from the high altitude burst. As discussed in Section III of the Course Notes - Third Edition, the EMP generation for the high altitude burst case (HEMP) results from Compton electron turning in the ionosphere. The EMP generated may be considered as a propagating plane wave below the ionosphere.

No EMP is radiated from the ionosphere into space. The EMP arriving at a satellite (or other space system), therefore, is due to a reflection from the earth's surface or a direct line of sight propagation path from the source region to the system.



In either case, the EMP propagates through the ionosphere. Since the ionosphere is an ionized medium, the transmissivity characteristics exhibit both attenuation and phase shift which are frequency dependent. The result is the amplitude and spectrum of the HEMP is drastically modified. For this reason, EMP at satellite altitudes is often referred to as dispersed EMP (DEMP). A typical satellite EMP signal resembles an amplitude modulated swept frequency signal.



AMPLITUDE AND INSTANTANEOUS FREQUENCY OF A TYPICAL SATELLITE EMP

The maximum amplitude of the EMP electric field is of the order of ten's of volts per meter. The frequency spectrum is approximately 15 MHz to 250 MHz. This environment is relatively benign as compared to the HEMP experienced below the ionosphere or the SREMP. It must, however, be considered as an interference source since the impact of any EM source is highly dependent on the irradiated systems characteristics.

Direct Radiation Interaction

The System Generated Electromagnetic Pulse (SGEMP) effects are of high concern in the case of space systems. As discussed previously, in cases where the system is located on the surface or near the surface of the earth, there is enough attenuation of x-rays by the atmosphere between the burst and system to reduce their significance and gamma rays are the dominant source. This condition is true even though the gamma ray output is a much smaller percentage of the weapon output than the x-rays. This is because gamma rays have photon energies of about 1 MeV as compared to 1 keV for thermal x-rays and therefore their absorption length is much longer than x-rays (several hundred times larger in air).

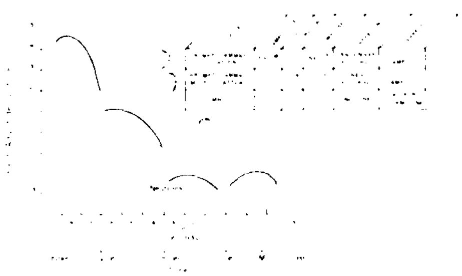
In the case of satellites (and other space vehicles) where the system and the nuclear burst are above the atmosphere, the x-rays are not attenuated. They therefore become the dominant source for SGEMP even though their energy is lower. This is because they make up a large fraction of the weapon output and also because the electron yield (photoelectrons) for emission from material/vacuum interfaces is usually largest at photon energies of a few keV.

The SGEMP problem was qualitatively discussed in the section entitled "Direct Radiation Interaction" and will not be repeated here. It should be remembered however, that the dominant source is different (x-rays) and therefore, SGEMP is a highly significant problem to satellites and space systems.

3.3 MHD EMP GENERATION

The magnetohydrodynamic (MHD) EMP is generated by hydrodynamic motions in the ionosphere, caused by a high-altitude nuclear explosion. Perturbations in the geomagnetic field are induced, and the time variation of the magnetic field generates electric fields. These electric fields, as observed at the earth s surface, are weak (tens of volts per kilometer), but they occur over long times (hundreds of seconds). The following figure compares the MHD EMP electric field amplitude

and time history to that of other types of EMP. Like high altitude EMP, MHD EMP covers large geographical areas (several hundreds of kilometers). Because of the long time history, these fields contain only extremely low frequency components and in many situations can be considered dc. Hence, MHD EMP fields are of possible significance only for long electrical lines (> 10 km) such as long communication lines.



TIME DURATION AND STRENGTH OF MHD EMP AS COMPARED TO OTHER HIGH ALTITUDE EMP EFFECTS

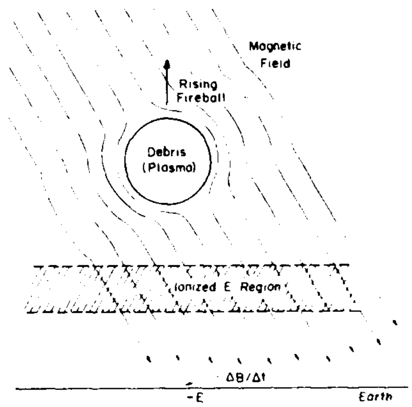
The theory of the MHD EMP is not yet totally understood. However, many of the mechanisms which contribute to MHD EMP in various degrees have been hypothesized. These phenomena include the rising fireball or magnetic bubble model, atmospheric motion, and beta tube currents.

Magnetic Bubble

The magnetic bubble model illustrates many of the basic ideas of MHD EMP. A nuclear burst will ionize the region of air surrounding it. This highly ionized region will also be heated and thus rise and expand as time progresses, according to the laws of hydrodynamics. Because it is highly conducting, this "bubble" will also force out any nearby geomagnetic field lines as it expands. One way to picture this is to imagine that the magnetic field lines are frozen in the plasma. Then, as the fireball expands, the lines get pushed out. A simple calculational model is thus a perfectly conducting sphere with a time varying radius immersed in the earth's magnetic field.

The net effect is a change in the electromagnetic field due to the earth's magnetic field being pushed out.

The E-region of the ionosphere below the burst is also indicated in the figure. This region extends roughly from 80 km to 140 km, depending upon the solar activity. The E-region conductivity is enhanced by ultraviolet, x-ray and beta radiation from the explosion, and hence the region is highly conducting. This conductivity effectively blocks observers on the ground from seeing the magnetic field variations occuring above it until deionization chemistry sufficiently reduces the E-region conductivity (on the order of 50 to 100 seconds). However, B-field variations due to motion of the E-region itself can be seen by ground observers at this time.



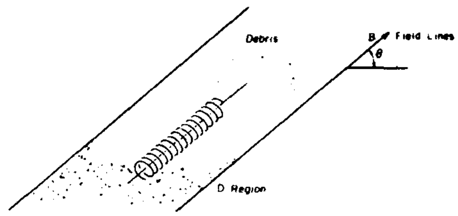
EXPANDING AND RISING FIREBALL OF THE MAGNETIC "BUBBLE" MODEL

Since this E-region is highly conducting it has the effect of partially or totally freezing the magnetic field lines within the plasma. Hence, any motion by this region - other than parallel to the magnetic lines - will cause B-field variations. The two basic types of motion in this region are thought to be atmospheric heave and shock wave propagation. Heave is the rising of large portions of the atmosphere due to heating by the x-ray and UV radiation. The shock waves are both the compressional hydrodynamical type (sound) and the transverse magnetohydrodynamical type (ALFVEN). The latter, which can have larger velocities, carry the first shock information to the lower atmosphere.

Beta Tube Currents

Another candidate source for the MHD EMP is the beta patch current drive by fireball polarization fields. This current occurs only when the ambient magnetic field is tilted away from normal to the earth. In such cases the rapid fireball rise has a component of velocity perpendicular to the magnetic field. Since a conductor is crossing the field lines the current tends to flow through the fireball to create a restraining force opposing this plasma motion. The extent to which this current flows is governed by the resistive properties of the plasma outside the fireball. If there is no return path for this current, a sufficiently large polarization field is set up such that the $\vec{E} \times \vec{B}$ drift velocity equals the component of the fireball velocity perpendicular to the geomagnetic field. The process is analogous to that which occurs in an ordinary generator in which the armature conductors move across field lines set up by stationary coil windings.

The beta patch is a layer of D-region ionization produced by delayed betas from radioactive fission fragments contained in the high altitude ($h > 100$ km) debris clouds. At such high altitudes scattering by air particles is negligible and hence, the motion of the betas is strongly influenced by the geomagnetic field. The betas spiral down the field lines into the atmosphere where they deposit their energy in ionizing collisions with air molecules. Thus, the beta patch and tube is just a projection of the debris cloud along geomagnetic field lines into the D- region. Since this projection is highly conducting it gives a conducting path for the currents to flow which were generated by the mechanism outlined in the previous paragraph, that is the rising fireball cutting the geomagnetic field lines. It is this current flowing in the beta tube which is thought to be a major source of MHD EMP fields.



GEOMETRY OF BETA PATCH AND TUBE FORMATION

The three mechanisms thought to contribute to the MHD EMP which have been briefly described all depend on the orientation of the earth's geomagnetic field lines in the burst region. In the U.S. the geomagnetic field is dominantly vertical, whereas in the Pacific it is dominantly horizontal. Thus, in the U.S. the atmospheric heave and beta tube currents would probably be very small compared to the rising and expanding of the fireball induced field changes. However, in the Pacific the opposite is likely to be the case.

SECTION IV

EMP INTERACTION AND COUPLING ANALYSIS

Assessment of the effects of the EMP environments discussed previously on a system requires an understanding of how the environment interacts with the system and the extent of this interaction. Section IV of the Third Edition of the Course Notes discussed the classical free field electromagnetic interaction and coupling analysis. The discussion in this section will supplement the basic course notes in that it will discuss the additional considerations necessary to treat the close-in region, the MHD EMP, and the space problem.

The material presented is somewhat simplified to provide insight into the problem in keeping with the goal of the course to provide EMP awareness. More details can be obtained by refering to the papers and reports listed in the bibliography.

4.1 SOURCE REGION EMP COUPLING

The classical EMP coupling problem involves electromagnetic fields which are generated in one part of space and propagate through an intervening medium to a system located in another part of space. The problem can be solved in three independent steps: EMP generation, propagation, and system coupling. The "source region" or "close-in" EMP problem, in its most extreme form, differs from the classical coupling problem in many ways, the most important of which is that the system itself cannot be excluded from the environment calculation.

When a system is in the EMP source region or deposition region of a nuclear detonation, i.e., close-in, the EMP environment interacts with the system. The Compton and/or photoelectric currents which drive the incident electromagnetic field become scattered or absorbed by the system and the incident gamma rays and x-rays produce Compton electrons and photoelectrons by interacting with the system and producing additional currents that would not exist if the system were not present. In addition, the Compton and photoelectric electrons ionize the atmosphere, producing secondary currents, thus surrounding the system with a time varying plasma. This means that EMP vulnerability studies of in-flight missiles that must traverse the high-altitude source region and ground based systems located in the source region of surface or near-surface bursts require analysis techniques above and beyond those used to study free field EMP coupling problems in the radiated region.

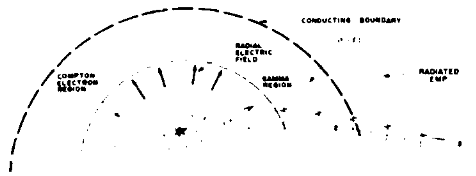
Thus, in the most extreme case, corresponding to regions of large air conductivity, it is imperative that the systems analyst have the capability to model both the system and the physics of EMP generation. The capability to understand the physics is important in modeling most close-in coupling problems, even if the EMP environment problem is not to be solved simultaneously with the coupling problem.

It should be noted that even if a system is not expected to survive in high overpressure regions, its response to EMP in those regions can be an important factor to consider. A long transmission line, for example, will be subjected to EMP before the shock wave reaches and destroys it. A current pulse will then flow along the transmission line to equipment located far from the burst, with the potential to cause permanent damage to electronic components.

These two cases are presented pictorially in the following figure. The strategic missile system is totally within the source region. Therefore, the interaction of the entire system with the gamma rays, Compton electrons, the electromagnetic fields and the effects of time varying air conductivity must be considered.

In the case of the long transmission lines, one user terminal is located within the gamma ray and Compton electron regions, a second user terminal is located within the conducting boundary, and the third terminal depicted is far removed from the burst point in the radiated EMP region. For the first terminal the effects of the electromagnetic fields, the conduction current, the Compton current and SGEMP must be considered. Even if this terminal is not designed to survive the close-in environment these interactions will result in a conducted transient at the other terminals. The second terminal will have induced currents due to the EM field and the conduction current due to the time varying air conductivity. The third terminal will only have the effects of the classical EMP coupling problem plus the currents conducted from the other two terminals along the transmission line.

These two cases exemplify the type of burst/system location considerations associated with source-region EMP interaction.



CLOSE - IN SYSTEM INTERACTION

EMP Environment Interaction

A system undergoes three basic types of electromagnetic interaction with its environment. First there is coupling with the electromagnetic fields themselves. When this is the dominant mechanism for interaction, we have the classical "antenna" type problem. This is the case outside the EMP source region where the EMP is a radiated field.

The second type of interaction is through the conductivity of the medium in which the system is immersed. The conductivity interaction is obviously not independent of the electric field interaction, since there would be no conduction current without an electric field. However, it is listed separately because of the significant changes which can occur in a system's response when the medium is conducting (either naturally conducting or ionized by weapon radiation). Classical coupling problems can consider systems in a medium of constant conductivity. The close-in coupling problem is distinguished by the fact that the conductivity of the medium (air) is time dependent and electric field dependent. Therefore, the coupling problem is nonlinear.

The concept of conductivity is useful only at low altitudes, where electron collisions are frequent enough to control the electrons motion, i.e., when its momentum can be ignored. In this case, the electron's velocity is proportional to the instantaneous value of the electric field. When the air density is lower, such as in the ionosphere, the conduction electrons gain a significant amount of momentum and energy between collisions and they cannot respond immediately to changes in the electric field. The same problem occurs in radiowave propagation. There, however, less energy is transferred from the fields because the fields are much smaller than EMP fields in the close-in region and therefore, the collision frequency can be considered independent of field strength. The conductivity (or equivalently, the dielectric constant) can be treated as a complex function of frequency. The electron current lags behind the fields by an amount which depends upon signal frequency. Transient problems can be solved under these conditions by Fourier transforming the pulse into the frequency domain. This is not always possible with EMP problems, because the dependence of the collision frequencies upon the total electric field prevents the decomposition of the transient into a spectrum of frequencies which can be treated independently.

The third type of system interaction is the direct interaction of the system with the nuclear radiation emitted by the burst (x-ray, gamma ray, neutron) and with the high energy Compton and photoelectric currents generated in the air and ground around the system. The initial nuclear radiation can produce additional interior fields (SGEMP) and TRE effects through interaction of the radiation with electronic components. Since a system usually employs conducting structures or elements (shelters, cables, etc.), Compton and photoelectric currents can be collected by the system resulting in enhanced total skin currents.

These three types of interaction affect Maxwell's equations. Essentially, they appear as three different driver current terms: displacement, conduction and radiation driver current. The simplicity of the equations conceals the difficulty of their solution in practical cases.

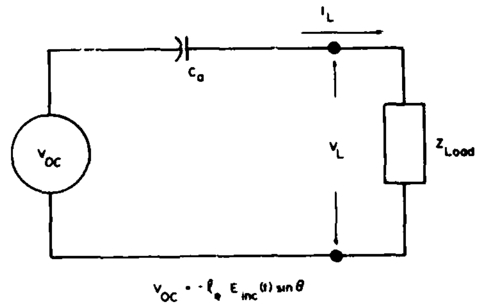
$$\nabla \times \vec{E} = -\mu \dot{\vec{H}}$$

$$\nabla \times \vec{H} = \underbrace{\underbrace{\epsilon \dot{\vec{E}}}_{\text{Displacement Current}}}_{\text{Sufficient for Free Space Coupling}} + \underbrace{\underbrace{\sigma \vec{E}}_{\text{Conduction Current}} + \underbrace{\vec{J}_c}_{\text{Compton Current}}}_{\text{Additional Current Terms Necessary for Close-in Coupling}}$$

Maxwell's Equations Showing Terms Necessary for Free Space Coupling and Close-in Coupling.

Coupling to Systems

In order to understand the nature of these interactions, consider the problem of the interaction of an electrically small vertical monopole antenna at various distances from a nuclear burst. This discussion will be aided by the use of electric circuit concepts and analogs. These concepts are familiar to all electrical engineers and are therefore useful for illustration purposes. In many cases they are also useful for systems response calculations. It must be emphasized, however, that a great deal of experience and knowledge is required in order to develop and utilize these circuit analogs effectively. The physics of the problem is much more complicated than that which is ordinarily encountered in an engineer's education and sufficient training cannot be obtained from a short course such as this. The models developed here are for aiding in the visualization of the interactions involved. They in no way constitute a recipe for solving realistic close-in coupling problems.



SIMPLIFIED THEVENIN EQUIVALENT CIRCUIT FOR A MONOPOLE ANTENNA

Effects of Time Varying Air Conductivity

The problem of coupling to a dipole or monopole is discussed in Section 4.4 of the basic Course Notes for the "free space" case. The voltages and currents developed across a load can be calculated through the use of a Norton or Thevenin equivalent circuit. A simplified Thevenin equivalent circuit for a monopole is shown in the figure. The antenna impedance is shown as capacitive (C_A) and the open circuit voltage (V_{OC}) is proportional to the tangential component of the electric field and the effective length (ℓ_e) of the antenna. For an electrically short antenna, the simple antenna capacitance is a good approximation, and the effective length for a monopole over a perfectly conducting ground plane is equal to the physical length. It should be noted for non-electrically-short antennas the effective length and impedance are complex functions (see Section 4.4). The discussion that follows assumes an electrically short antenna.

Beginning with the EMP source region coupling problem which most resembles the free-space situation, consider the antenna to be located in the outer region of the gamma deposition region where the peak air conductivity is low, but not negligible, i.e., skin depths in the plasma are much greater than the antenna dimensions, and radiation levels in the vicinity of the antenna are too low to generate significant local electric fields or to cause significant charging of the antenna through direct interaction. The antenna will interact with the electromagnetic fields generated between the burst and the antenna. The reaction of the antenna is modified from the free space case by the time-dependent conductivity.

The term "skin depth" can only be defined in terms of frequency. Since time dependent transients are involved, it is necessary to define a time dependent quantity which will serve the same general purpose as skin depth, i.e., give some idea of how far fields penetrate into the plasma before they are attenuated. Beyond this distance, the plasma does not react to the antenna and the antenna does not see fields generated in the plasma. Such a characteristic distance depends upon the time waveform of the transient. However, reasonable estimates can be made using the following formula for the characteristic distance [p(t)]:

$$p(t) = \sqrt{\frac{2t}{\mu\sigma(t)}} \quad \text{(meters)}$$

where

σ is the conductivity of the medium (air), mho/m

μ is the permeability ($\mu = 4\pi \times 10^{-7}$ henry/m for free space

t = time

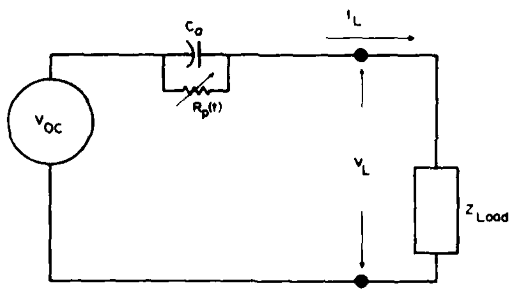
ω is angular frequency (radians/sec).

This is simply the skin depth formula with ω, the frequency (radians/second), replaced by $1/t$. It is reasonably accurate for the penetration distance of a step function field in a medium of constant conductivity. For this discussion, a time dependent conductivity has been allowed in the formulation.

The electric fields associated with the capacitance of the antenna are concentrated within a distance on the order of the antenna dimensions. When $p(t)$ is large compared to the antenna dimensions, its capacitance will change negligibly, but a "leakage" resistance will be introduced across it. The equivalent circuit for an antenna on the fringes of the deposition region is then the same as before, except that a time dependent leakage resistance appears across the free space capacitance C_A. This resistance, $R_p(t)$ can be estimated from the conductivity and antenna capacitance through the relation

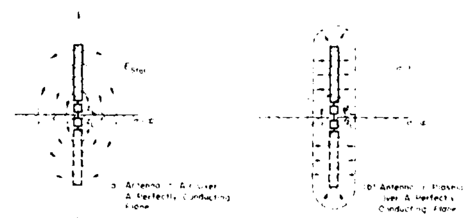
$$R_p C_A = \varepsilon_0/\sigma$$

where ε_0 is the permittivity of free space (8.854×10^{-12} farad/m). This relation assumes that any effects associated with the flow of current through the surface of the antenna can be ignored, and this is not always a good assumption. In reality, the effective resistance can be much larger and can even vary with the direction of current flow.



SIMPLIFIED THEVENIN EQUIVALENT CIRCUIT FOR A MONOPOLE IN REGION OF TIME VARYING CONDUCTIVITY

Next consider the case where the antenna is closer to the burst and that $p(t)$ is on the order of the antenna dimensions. In this case, the field lines corresponding to the capacitance of the monopole, i.e., the "static" fields associated with the charge distribution on the antenna, are distorted by the presence of the plasma. When $p(t)$ is small, the antenna capacitance then changes from one that represents coupling between the antenna and its image to one which represents coupling between it and the plasma. This capacitance can be modeled as the coupling between the antenna and a metallic cylinder a characteristic distance away. The distance $p(t)$ can be used as a first approximation but it should be remembered that the characteristic distance will depend on time derivatives of the fields and on their magnitudes (through the field dependence of the conductivity). The figure illustrates this concept. The cylinder to which the field lines attach is filled with the conducting plasma. The equation relating R_p, C_A and media parameters remains valid. However, the capacitance is now time dependent, i.e., $C_A = C_A(t)$, because the effective dimensions of the cylinder vary with time.



SCHEMATIC REPRESENTATION OF MONOPOLE ANTENNA CAPACITANCE

An estimate of the time dependent capacitance of the monopole can be made as follows. Assume a monopole with height, h, and radius, a, where a << h. As shown in the figure, the plasma causes some of the electrical field lines that were linked to the image of the antenna in the ground to be linked to the plasma. A return path occurs from the image plasma to the image antenna. For this

discussion, assume that all field lines go radially into the plasma, which is represented as a coaxial cylinder a distance p(t) away. This distance must be small compared to h or else the free space capacitance will dominate, i.e., most field lines will connect with the image in the ground.

Assuming a coaxial cylinder of length 2h, the antenna capacitance in the presence of a plasma is given by

$$C_A(t) = \frac{4\pi\varepsilon_o h}{\ell n[p(t)/a]}$$

The capacitance of a thin monopole over a ground plane (a << h) is approximately

$$C_m = C_A(\text{free space}) = \frac{4\pi\varepsilon_o h}{\ell n(2h/a)}$$

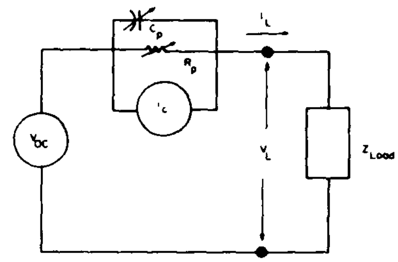
Thus, when p(t) exceeds 2h, the free space capacitance must be used.

The calculation of $\sigma(t)$ is fairly complicated in general, since electric field dependent quantities are involved. Estimates are best obtained from EMP environment handbooks. It should be noted that radiation levels, as a function of distance from the burst and weapon yield, do not scale in the same way as overpressure levels. For the same overpressure level, a small yield burst provides a greater radiation level than a larger yield burst.

Effects of Direct Interaction

In regions of high conductivity the antenna will also be subject to Compton currents and gamma radiation, as previously mentioned. The antenna can then collect charge directly from its environment. This can be the main driver of currents through the load. The amount of charge collected will depend upon how transparent the system is to gamma rays, i.e., how well gamma radiation penetrates without attenuation. An antenna which stops all radiation (opaque) will simply collect all the Compton current which strikes it. As it charges up, it will begin to deflect the Compton electrons away from it. If the antenna is transparent the gamma rays cause a Compton current to flow off of the back which reduces the net charge caused by the collection of Compton current in the front.

The figure illustrates a circuit analog of the antenna problem just described. The current drive, i_c, appears across the antenna capacitance/leakage resistance elements. As an upper limit, i_c can be estimated by taking the Compton current density (amp/m^2) obtained from an EMP environment calculation and multiplying it by the cross sectional area of the system. Comparing this with the conduction current (σE) will indicate whether the direct interaction drive could be important.



SIMPLIFIED THEVENIN EQUIVALENT CIRCUIT FOR A MONOPOLE INCLUDING COMPTON CURRENT SOURCE

Application of Circuit Modeling Technique

The circuit modeling technique, illustrated here, is one which is often used to solve close-in coupling problems. It requires a great deal of experience to use and even then it is possible to leave out some part of the physics or to model it badly. Computer codes are available to solve certain types of problems. Many problems require a three dimensional calculation, even if the system has cylindrical symmetry and would require only a two dimensional calculation for the free space scattering problem. This is because the calculation of the close-in scattering problem requires currents and conductivity to be calculated in the air around the system. These sources develop behind a plane wavefront of gamma rays which sweeps across the system. The problem is two dimensional only if the wavefront sweeps down along the axis of the cylinder. A large amount of storage is required because of the number of quantities that must be computed and the number of positions at which they must be computed. In order to calculate a field dependent current, "particles" must be followed. These represent groups of electrons and

obey the electrons equation of motion in the presence of electric and magnetic fields. At each time step the net motion of the particles in a computational cell is used to compute the Compton current. While these codes are complicated and limited in the amount of detail they can incorporate into the system model, they do include all of the physics.

4.2 EMP COUPLING AT SATELLITE ALTITUDES

As discussed in Section 3.2 of this supplement, the EMP at satellite altitudes is a propagated EM wave whose characteristics have been modified due to propagation through an ionized media. Also, in some instances, the field characteristics are modified by the reflection characteristics of the earth. Both effects are frequency dependent. The earth reflection coefficient is, in addition, a function of the angle of arrival and the polarization of the incident wave, and the conductivity and permeability of the earth. The transmission through the ionized media is also a function of the degree of ionization.

These effects both attenuate and phase shift the incident signal. The result is a considerable distortion of the EMP signal. The signal is, however, still a propagating EM wave.

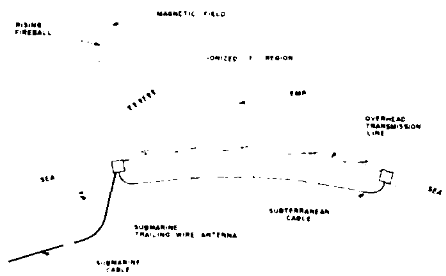
Since the wave in the space region is a propagating wave, the coupling considerations are the same as for any propagating EM wave as discussed in Section 4.4 of the Third Edition. The primary difference is the definition of the fields as a function of time, i.e., calculating E(t) and H(t) in the vicinity of the system of interest.

As stated previously, the EMP signal is a low amplitude ringing signal with predominantly high frequencies. Unless the system of interest shows a strong response, such as a system designed to operate at one or more of these frequencies and has deliberate resonant antennas, the effects of the EMP are rather weak. The predominant threat to space vehicles (satellites, RV's, etc.) is the x-rays emitted by the nuclear detonation. This is in essence the SGEMP problem. A discussion of the SGEMP coupling problem is beyond the scope of this document but can be found in the references cited.

4.3 MHD EMP COUPLING

The spectral content of the magnetic and electric fields produced by MHD EMP is in the near dc to a few Hertz frequency range. Because of this low frequency and the small amplitudes of these fields only systems employing long electrical conductors are of concern in studying coupling effects of MHD EMP. Also, low frequency fields have very large penetration depths in both water and soil. Hence, if long buried cables or submarine cables are present under the burst regions it is likely that substantial voltages will be induced between their underground conductors and ground. That is, the ground or water will not serve as a protection device as it does against high altitude EMP. If the induced voltages become high enough, typical cable systems will shut themselves down.

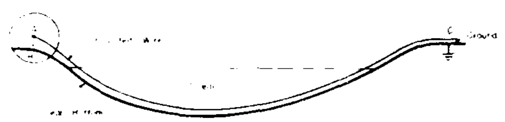
Typical system configurations of concern with regard to MHD EMP coupling are depicted pictorially in the following figure.



MHD EMP COUPLING

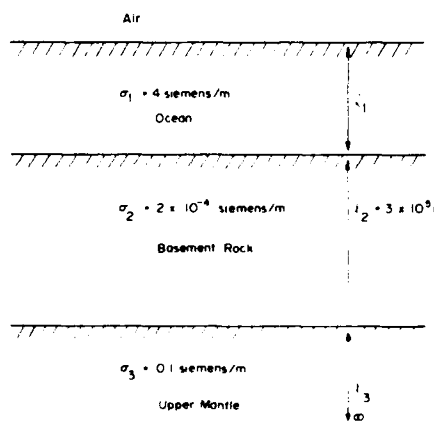
As an example of how MHD EMP coupling to long cables may be analyzed, coupling to a long undersea cable will be discussed. The configuration which will be studied is shown in the figure. Assume that an insulated wire lies on the ocean bottom, connecting points A and C. Both A and C will normally be on an island or continent, close to the shoreline. Assume that the wire is grounded at point C, but not at point A. Hence, the voltage, V_{AB}, between the end of the wire A and ground B is the voltage of interest.

To calculate this voltage, it is necessary to know the value of the electric field in the absence of the wire along the ocean bottom. If the horizontal H field at the surface of the ocean can be estimated or measured, then the fields within the ocean, and particularly at the



SUBMARINE CABLE CONFIGURATION

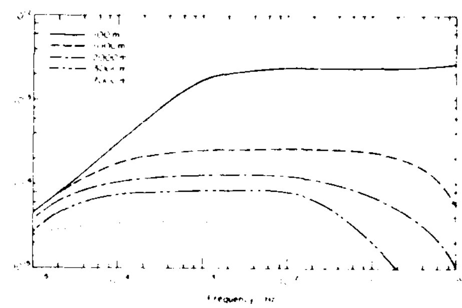
ocean floor, can be found by solving Maxwell's equations. The equations of interest will not be written here. However, basically what happens is that the magnetic field diffuses into the conducting sea and induces an electric field in the water. This electric field then couples to the cable as described below.



STRATIFIED OCEAN EARTH MODEL

Since the cable is assumed to be on the ocean floor it is necessary to know the properties of the ocean floor as well as those of the ocean. Shown is a typical stratified ocean-earth model which could be used to determine the induced E fields at the ocean's floor.

The following presents the magnitude of the electric fields at the ocean bottom for different ocean depths of the stratified model when the surface H field magnitude is one ampere per meter. These results were obtained by solving the diffusion equation in the presence of stratified media. As would be expected the fields attenuate as a function of depth and frequency.



MAGNITUDE OF ELECTRIC FIELDS AT THE OCEAN BOTTOM FOR DIFFERENT OCEAN DEPTHS WHEN THE SURFACE H FIELD MAGNITUDE IS ONE AMPERE PER METER

To determine the electric field at the bottom of the ocean due to the MHD EMP, one simply multiplies the spectrum of the surface MHD EMP H field in amperes per meter-Hertz times the desired spectral curve in the figure.

Once the electric field $\vec{E}_b$ in the absence of the wire at the bottom of the ocean is known then the loop potential, V_{AB}, can be determined. This is achieved by applying Faraday's law of induction to the closed loop defined as follows: start at A, go along the wire surface (inside the insulation) to the point C, back to the point B along the ocean bottom (just outside the insulation), and then across the gap from B to A. Since this loop contains negligible magnetic flux the intergral of the electric field around the loop will vanish. Since the electric field is zero at the wire surface the integral along the wire surface will vanish also. Therefore, the only remaining terms are

$$V_{AB} = \int_C^B \vec{E}_b \cdot dl$$

Thus it is the integral of $\vec{E}_b$ along the ocean bottom (path of the cable) that determines the open circuit voltage V_{AB}.

If the cable is grounded at both ends a current, $I = V_{AB}/R$, will flow through the wire, where R is the resistance of the wire. If neither end of the wire is grounded then the integral of the field along the bottom will equal the difference in voltage from wire to ground at the two ends.

The approximate induced voltage on a 100 km line is on the order of 1 kV. This illustrates that unless very long conductors are employed in a system, the voltage induced due to MHD EMP is much less than would be experienced due to other types of EMP.

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